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Estimating the impacts of climate change on crop yields and N_2O emissions for conventional and no-tillage in Southwestern Ontario, Canada

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ABSTRACT

Accurately predicting the impacts of higher temperatures, different precipitation rates and elevated CO_2 concentrations on crop yields and GHG emissions is required in order to develop adaptation strategies. The objectives of this study were to calibrate and evaluate a regionalized denitrification-decomposition (DNDC) model using measured crop yield, soil temperature, moisture and N_2O emissions, and to explore the impacts of climate change scenarios (Representative Concentration Pathways (RCP) 4.5 and RCP 8.5) on crop yields and N_2O emissions in Southwestern Ontario, Canada. This simulation study was based on a winter wheat-maize-soybean rotation under conventional tillage (CT) and no tillage (NT) practices at Woodslee, Ontario, Canada. The model was calibrated using various statistics including the d index (0.85–0.99), NSE (Nash-Sutcliffe efficiency, NSE > 0) and nRMSE (normalized root mean square error, nRMSE < 10%) all of which provided "good" to "excellent" agreement between simulated and measured crop yields for both CT and NT practices. The calibrated DNDC model had a "good" performance in assessing soil temperature. However, there were no differences in simulated soil temperatures between CT and NT treatments and this was attributed to deficiencies in the temperature algorithm which does not consider the insulation effect of surface crop residues in the DNDC model. The DNDC model provided a reasonable prediction of soil water content in the 0–0.1 m depth, but it overestimated soil water content during dry conditions mainly because the model was unable to characterize preferential flow through clay cracks. Under future climate scenarios, soybean and maize yields were significantly increased compared to the baseline scenarios due to the benefits from higher optimum temperature for maize and increased CO_2 for soybean. The mean annual N_2O emissions for winter wheat significantly increased by about 38.1% for CT and 17.3% for NT under future RCP scenarios when using the current crop cultivars. However, when a new cultivar with higher TDD (thermal degree days) was used, the mean winter wheat yield increased by 39.5% under future climate scenarios compared to current cultivars and there were significant reductions in N_2O emissions. The higher crop heat units cultivars and longer growing season length would contribute to increased biomass accumulation and crop N uptake. Hence there would be co-benefits with the development of high TDD cultivars in the future as they would not only increase crop yields but also reduce N_2O emissions.

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1. Introduction

Dynamic crop and soil models are widely used in agricultural systems to provide a detailed estimation of crop growth, nutrient cycling and water movement (Tsuji et al., 1998; Liu et al., 2011; Li et al., 2015a,b). Many soil and crop models have been used to estimate cultivar performance and optimize management practices under different climatic conditions (i.e., humid, semi-arid, dryland regions) and cropping systems (i.e., monocropping, rotation) (Jeuffroy et al., 2013; Uzoma et al., 2015; He et al., 2016). They have also been used to predict the impacts of future climate change scenarios on crop production, greenhouse gas emissions and water quality (Xu-Ri et al., 2012; Smith et al., 2013a; Wang et al., 2015). The DNDC (Denitrification–Decomposition) (Li et al., 1992a,b) model is a process-based model which is capable of simulating soil fluxes of agricultural greenhouse gases (e.g.,

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nitrous oxide, carbon dioxide) as well as other important crop and soil factors including crop yields, soil water, temperature and nitrate leaching (Ludwig et al., 2011; Li et al., 2012; Deng et al., 2016).

Global greenhouse gas (GHG) emissions increased from 1970 to 2010 with larger absolute increases between 2000 and 2010 due to human activities such as fossil fuel combustion, land use change, deforestation and cement production (IPCC, 2014). Increasing concentrations of GHGs is likely to increase temperatures, change precipitation patterns and increase the frequency of extreme events (Islam et al., 2012). Greenhouse gas emissions have increased by about 70% overall from 1970 to 2010 with carbon dioxide (CO_2) being responsible for nearly 78% of this increase as one of the largest contributing GHGs (IPCC, 2014). Agricultural crop production is likely to be markedly impacted by changes in the atmospheric CO_2 concentrations, temperature and precipitation because of the variations in photosynthesis, respiration rates, water use efficiency and soil C and N biochemical transformations (Wang et al., 2014; Long et al., 2015).

Conventional tillage (CT) management practices (moldboard plowing) can have negative effects on soil nutrient loss and can cause the degradation of soil structure as well as increased greenhouse gas emissions (Chen et al., 2011; Liu et al., 2013; Drury et al., 2006, 2012). Compared with CT, conservation tillage practices (i.e., reduced tillage, zone tillage, no tillage etc.) can reduce water and wind erosion, increase soil water use efficiency and improve soil quality such as increased near-surface organic matter content, improved microbial activity and decreased fuel and labour input costs (Huggins and Reganold, 2008; McLaughlin et al., 2008; Yang et al., 2008; Shi et al., 2012; Ziadi et al., 2014; Chi et al., 2016). Conservation tillage can impact CO_2 and N_2O emissions depending on different cropping practices and local soil and climatic variations (Drury et al., 2006; Rochette et al., 2008; Chi et al., 2016).

The DNDC model has been successfully applied to several studies under different tillage systems. Farahbakhshazad et al. (2008) conducted sensitivity analysis using the DNDC model in a corn-soybean rotation system in Iowa during a 20 year period, and no-tillage practices were found to significantly increase SOC storage and reduce N leaching rate, but slightly decreased crop yields and increased N_2O emissions. A similar sensitivity study reported that conventional tillage with a tillage depth of 20 cm elevated N_2O emissions in a winter wheat-maize rotation system in China (Li et al., 2010). In contrast, the DNDC model underestimated N_2O fluxes up to 55% from reduced tillage plots in Ireland due to an overestimation of the water filled pore space and the effect of SOC on the flux (Abdalla et al., 2009). In addition, Beheydt et al. (2008) reported that the DNDC model showed a significant overestimation of N_2O emissions for CT practice and an underestimation for minimum tillage in a Belgium maize study. The differences in performance of the DNDC model were mainly due to uncertainties in model parameterization and calibration, and limitations in model inherent structure, as well as the differences in soil types, management practices and climatic conditions (Ludwig et al., 2011).

Winter wheat-maize-soybean rotation is a common practice in Southwestern Ontario, Canada. In previous studies, crop rotation could reduce the amount of N_2O emissions released from soil compared with monoculture cropping (Drury et al., 2008). In addition, tillage practices have been found to influence greenhouse gas emissions; conservation tillage could decrease N_2O emissions by 15–40% compared with conventional tillage (Drury et al., 2006; Drury et al., 2012). However, DNDC has not been previously used to evaluate a winter wheat-maize-soybean rotation under different tillage practices in Canada. It is essential to calibrate and evaluate DNDC model performance under different tillage practices. This information can then be used to develop best management practices and it could also be used to examine the impacts of climate change on crop production and environmental risks. Hence, the objectives of this study were to: (1) calibrate and evaluate a regionalized Canadian version of the DNDC model using measured crop yields, soil temperatures, water contents and N_2O emissions; and (2) explore the impacts of climate change on crop yields and N_2O emissions for a winter wheat-maize-soybean rotation under conventional tillage and no tillage systems in Southwestern Ontario, Canada.

2. Materials and methods

2.1. Field experiment

The field experiment was established in the fall of 1999 at Woodslee, Ontario, Canada (42°21′N, 82°75′W). The mean annual temperature was 9.3 °C with a 50-yr average annual precipitation of 843 mm. The soil is a Brookston clay loam with an average soil texture (0–0.15 m) of 28% sand, 35% silt and 37% clay. The soil physical and chemical properties were measured (Table 1) at the beginning of the field experiment as reported by Drury et al. (2006, 2012). Different tillage treatments were evaluated in this study. The crop rotation was winter wheat-maize-soybean with each phase of rotation present in each year in three adjacent fields. There were two tillage treatments with four replicates and each plot was 20 m long by 9 m wide. The tillage practices included conventional tillage (CT) (fall moldboard plowing with a secondary tillage in the spring) and no tillage (NT). The experimental design was a split-plot randomized complete block with the main plot units being tillage treatment and a factorial combination of two fertilizer dates (at planting and sidedress) (Drury et al., 2006, 2012).

Winter wheat (AC Essex) was planted at a seeding rate of 400 seeds m^{-2} in 7 cm rows. Fertilizer (6-24-24) was applied to the winter wheat phase just before planting to provide 12 kg N ha^{-1} and an additional 71 kg N ha^{-1} was applied in the spring. Maize was planted at a seeding rate of 7.6 seeds m^{-2} in 76 cm rows. When maize was planted, a starter fertilizer was applied (8-32-16) to provide 22 kg N ha^{-1}, 88 kg P_2O_5 ha^{-1}, and 44 kg K_2O ha^{-1}. The starter fertilizer was applied in bands that were 5 cm beside and 5 cm below the seed, which is composed of urea, monoammonium phosphate, and KCl. During the 6 to 8 leaf growth stage, 160 kg of N ha^{-1} from 2000 to 2002 and 130 kg of N ha^{-1} from 2004 to 2006 was applied to corn as a sidedress N fertilizer. Soybean was planted at a seeding rate of 61.5 seeds m^{-2} without fertilizer application. Management practices and planting/harvest dates are listed in Table 2. In this experiment, soil temperature (0–0.1 m) was measured during each growing season using a HI93510 thermometer (Hanna Instruments Canada Inc., Laval, Quebec). Gravimetric soil water content (0–0.1 m) was measured three times per week and determined on grab samples in the laboratory. Soil core samples (0–30 cm depth) were collected at the beginning, middle, and end of the growing season from each treatment to determine inorganic soil N (NH_4^+ and NO_3^-). Nitrous oxide emissions were measured a total of 106 times during the growing season in the corn phase of the rotation over six years using 48 rectangular acrylic field chambers, which consist of a "collar" (internal dimensions of 53.5 cm length, 17.7 cm width, 15 cm height) fitted with a removable gas-tight LiO. Detailed measurement information is described in Drury et al. (2006, 2012).

2.2. DNDC model

The DNDC model (Denitrification–Decomposition) is a process-oriented model describing carbon and nitrogen biogeochemistry in agroecosystems. It has been widely used to simulate greenhouse gas emissions, crop growth, C and N dynamics and soil water balance under different management practices and weather conditions (Li et al., 1992a,b; Ludwig et al., 2011; Li et al., 2012; Smith et al., 2013a; Abdalla et al., 2014). The DNDC model consists of two components. The first component consists of soil, climate, crop growth and decomposition sub-models which are used to predict crop growth, soil temperature, soil water content as well as soil C and N dynamics and these are modelled on a daily basis. The second component is based upon nitrification, denitrification and fermentation sub-models and these are used to simulate trace gases emissions from plant-soil systems including

Table 1
Soil physical and chemical data[a] of the experimental field for DNDC simulations at Woodslee, ON, Canada.

Soil depth (m)	Field capacity ($m^3\ m^{-3}$)	Wilting point ($m^3\ m^{-3}$)	Saturation ($m^3\ m^{-3}$)	Bulk density ($g\ cm^{-3}$)	Organic carbon (%)	pH	Silt content (0.05–0.005 mm) (%)	Clay content (<0.002 mm) (%)
0.0–0.15	0.412	0.119	0.475	1.46	1.85	6.1	34.8	37.4
0.15–0.30	0.445	0.121	0.482	1.55	1.37	6.2	33.6	38.3
0.30–0.45	0.399	0.122	0.453	1.57	1.15	6.2	32.2	40.5
0.45–0.60	0.382	0.122	0.445	1.57	1.03	6.2	32.2	40.5
0.60–0.90	0.385	0.126	0.454	1.57	0.41	6.2	32.2	40.5
0.90–1.20	0.384	0.136	0.435	1.57	0.41	6.2	32.2	40.5

[a] These soil data were measured by Drury et al. (2006, 2012).

carbon dioxide (CO_2), nitrous oxide (N_2O), nitric oxide (NO), methane (CH_4), ammonia (NH_3) and dinitrogen (N_2) on a daily basis (Li et al., 1992a,b; Li et al., 2012; Uzoma et al., 2015; Deng et al., 2016).

A modified version of the DNDC was developed for predicting the effects of agricultural management practices and climatic change on GHG emissions and crop growth at various locations and climate conditions in Canada (Smith et al., 2013a; Uzoma et al., 2015). Recent modifications to the DNDC model improved its ability to assess crop yields under local conditions for our study including: (1) the development of new crop growth curves to represent maize, wheat and soybean cultivars in cool weather conditions; (2) the effect of CO_2 fertilization and temperature stress on crop growth; (3) the influence of elevated CO_2 concentrations on water use efficiency; and (4) the adjustment of the C:N ratio of crop fractions in response to elevated CO_2, and from the impacts of elevated CO_2 on nitrogen use efficiency. These modifications are described in greater detail by Smith et al. (2013a) and Uzoma et al. (2015).

The DNDC model requires the following input data: (1) daily weather data, such as daily maximum and minimum air temperature (°C), daily solar radiation ($MJ\ m^{-2}$), and daily precipitation (mm) data; (2) initial soil conditions (e.g., soil organic carbon, soil nitrate and ammonium N content); (3) soil data (e.g., soil water at field capacity, wilting limit, soil bulk density, soil pH, and soil texture); and (4) agricultural management data (e.g., planting dates, harvest dates, crop parameters, tillage, fertilizer rates and types). The local meteorological data during the experimental period were acquired from the Woodslee weather station (42°13′N, 82°14′W). Daily temperature, precipitation and solar radiation from 1999 to 2006 are shown in Fig. S1. The measured initial soil water content (0–0.15 m) was 0.283 $m^3\ m^{-3}$, organic carbon was 18.5 $g\ kg^{-1}$, and the C/N ratio was 13:1 (Drury et al., 2006, 2012).

In this study, CT and NT treatments were evaluated using the DNDC model. The model was initially parameterized based on the measured crop growth information, initial soil physical and chemical properties, management practices and local weather data. In this DNDC simulation, continuous crop rotation was used to simulate multi-year soil and water dynamics in addition to crop growth processes. Initial soil conditions are only required to be set up before the first year simulation, then soil water, carbon and nitrogen flows are transferred to the next season automatically. The crop parameters for winter wheat, maize, and soybean were calibrated using measured crop yields. For this study, the yields from 2000 to 2002 were selected to calibrate the model and the yields from 2003 to 2006 were used to evaluate the model. However, yield data in 2000 and 2001 for soybean was not available so soybean yields from 2002 to 2004 were used to calibrate the model and from 2005 to 2006 to evaluate the model. The calibrated DNDC model was then used to simulate daily soil water contents, soil temperature as well as N_2O emissions.

2.3. Model performance statistics

To evaluate the DNDC model's performance, four deviation statistics were employed to compare the simulated and measured crop yields,

Table 2
Field experiment practices for winter wheat, maize and soybean at Woodslee, ON, Canada.

Year	Cultivar	Plant density (seeds m^{-2})	Row space (cm)	Planting (date)	Harvest (date)	Fertilizer application ($kg\ ha^{-1}$)			
						Starter			Sidedress
						N	P_2O_5	K_2O	N
Maize									
2000	N58D1	7.6	76	02-Jun	15-Nov	22	88	44	160
2001	N58D1	7.6	76	07-May	09-Nov	22	88	44	160
2002	N58D1	7.6	76	23-May	23-Oct	22	88	44	160
2003	N58D1	7.6	76	25-May	12-Nov	22	88	44	160
2004	N45A6	7.6	76	07-Jun	15-Nov	22	35	33	130
2005	N58D1	7.6	76	11-May	31-Oct	22	35	33	130
2006	N58D1	7.6	76	29-May	27-Nov	22	35	33	130
Wheat									
1999	AC Essex	400	7	16-Oct	19-Jul	12	0	0	71
2000	AC Essex	400	7	23-Oct	17-Jul	12	0	0	71
2001	AC Essex	400	7	15-Oct	25-Jul	12	0	0	71
2002	AC Essex	400	7	12-Oct	29-Jul	12	0	0	71
2003	AC Essex	400	7	21-Oct	22-Jul	12	0	0	71
2004	AC Essex	400	7	01-Nov	15-Jul	12	0	0	71
2005	AC Essex	400	7	28-Oct	21-Jul	12	0	0	71
Soybean									
2002	S2075	61.5	15	15-Jun	06-Oct	0	0	0	0
2003	S2075	61.5	15	17-Jun	08-Oct	0	0	0	0
2004	92M91RR	61.5	15	21-Jun	28-Oct	0	0	0	0
2005	92M91RR	61.5	15	26-May	24-Oct	0	0	0	0
2006	92M91RR	61.5	15	22-Jun	12-Oct	0	0	0	0

Table 3
The calibrated crop parameters at Woodslee, ON, Canada.

Crop	Cultivar	Biomass fraction			Thermal degree days	Water demand (g water g^{-1} DM)	N fixation index	Optimum temperature (°C)
		Grain	Leaf and stem	Root				
Winter wheat	AC Essex	0.42	0.41	0.17	1300	200	1.0	22
Maize	N45A1	0.52	0.33	0.15	2800	180	1.0	30
Maize	N58D1	0.45	0.40	0.15	2900	200	1.0	30
Soybean	S2075	0.43	0.41	0.16	1500	170	1.9	25
Soybean	92M91RR	0.48	0.40	0.12	1500	150	1.9	25

soil temperatures, soil moisture and N_2O emissions. The deviation statistics calculated (see Eqs. 1–4 below) include the mean bias error (MBE), normalized root mean square error (nRMSE), Nash-Sutcliffe efficiency (NSE) and index of agreement (d) (Willmott, 1982; Moriasi et al., 2007; Moriasi et al., 2007).

$$\mathrm{MBE} = \frac{\sum_{i=1}^{n}(S_i - M_i)}{n} \quad (1)$$

$$\mathrm{nRMSE} = \frac{\sqrt{\sum_{i=1}^{n}(S_i - M_i)^2/n}}{\bar{M}} \times 100 \quad (2)$$

$$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{n}(S_i - M_i)^2}{\sum_{i=1}^{n}(M_i - M)^2} \quad (3)$$

$$d = 1 - \frac{\sum_{i=1}^{n}(S_i - M_i)^2}{\sum_{i=1}^{n}\left(|S_i - \bar{M}| + |M_i - \bar{M}|\right)^2} \quad (4)$$

where S_i is the simulated value, M_i is the measured value, $i = 1, \ldots, n$ is the number of measured values, and $\bar{M}$ is the mean of the measured values.

The MBE value is the difference between the mean of the simulated variable and the measured variable. It can be used to evaluate whether the model significantly overestimates (MBE > 0) or underestimates (MBE < 0) the measured data based on the paired *t*-test (Willmott et al., 1985; Yang et al., 2000; Li et al., 2015a,b). The nRMSE (%) statistic is used to compare simulation performance among different state variables with different units (Priesack et al., 2006). There are no general agreement criteria for nRMSE (Liu et al., 2013). In this study, we consider an "excellent" match between simulated and measured data when nRMSE ≤ 10%, a "good" match when 10% < nRMSE ≤ 20%, a "fair" match when nRMSE 20% < nRMSE ≤ 30%, and a "poor" match when nRMSE > 30%.

The NSE (−∞ to 1) is a normalized measure that determines a relative magnitude of model residuals compared to the measured variance (Nash and Sutcliffe, 1970; Moriasi et al., 2007). A NSE value = 1.0

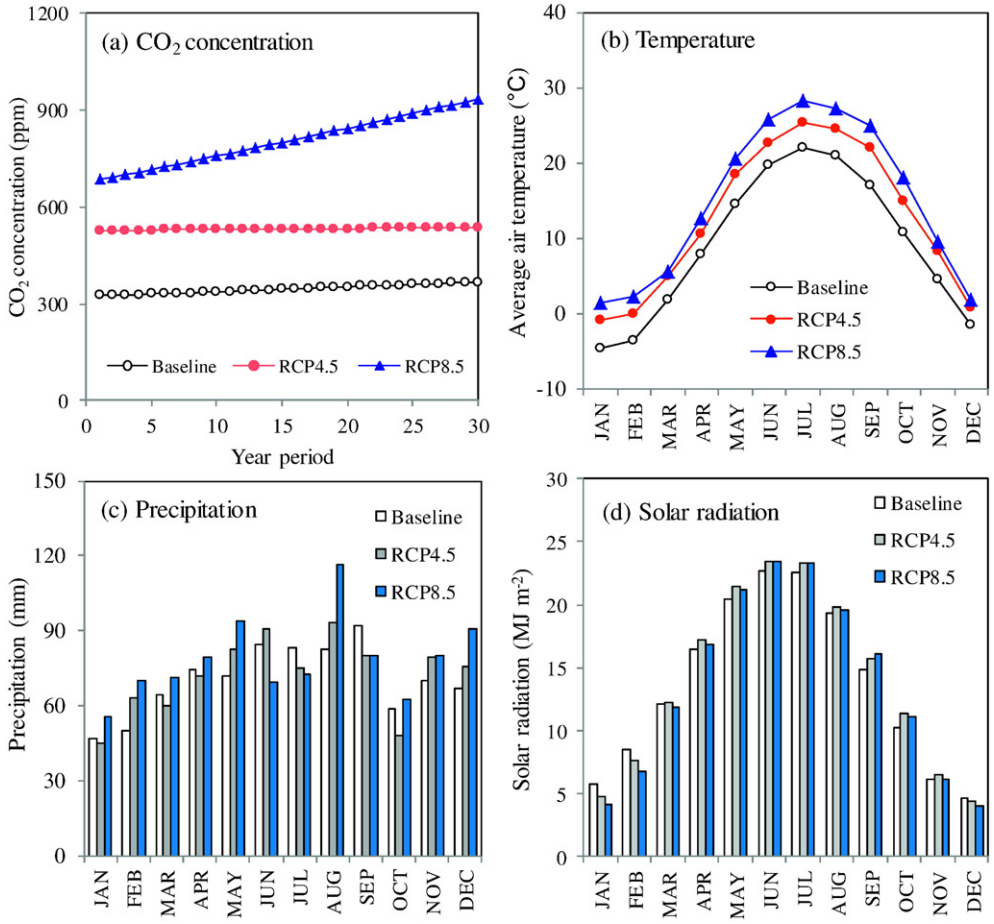

Fig. 1. Climate variables under Baseline (1971–2000), RCP4.5 (2071–2100) and RCP8.5 (2071–2100) scenarios at Woodslee, ON, Canada.

Table 4
Statistical evaluation between the simulated and measured crop yields under conventional tillage (CT) and no tillage (NT) using the DNDC model at Woodslee, ON, Canada.

Crop	Treatment	Time period	Measured yield[a] kg C ha^{-1}	Simulated yield kg C ha^{-1}	MBE kg ha^{-1}	Paired *t* (p)	nRMSE %	NSE	d	Sample no.
Calibration										
Winter wheat	CT	2000–2002	1587 (172)[b]	1540 (142)	−47	0.203	4.4	0.79	0.94	4
	NT	2000–2002	1445 (151)	1539 (142)	94	0.055	7.5	0.32	0.85	4
Maize	CT	2000–2002	3055 (480)	2985 (305)	−70	0.562	5.2	0.83	0.94	3
	NT	2000–2002	2925 (293)	2985 (305)	60	0.294	2.9	0.88	0.97	3
Soybean	CT	2002–2004	940 (272)	982 (283)	42	0.176	5.4	0.95	0.99	3
	NT	2002–2004	943 (303)	1022 (242)	79	0.154	9.9	0.86	0.96	3
Evaluation										
Winter wheat	CT	2003–2006	1576 (126)	1525 (112)	−52	0.095	3.6	0.69	0.92	3
	NT	2003–2006	1449 (143)	1520 (104)	71	0.105	5.5	0.54	0.86	3
Maize	CT	2003–2006	3141 (423)	3064 (448)	−80	0.831	3.0	0.93	0.98	4
	NT	2003–2006	2941 (428)	3097 (405)	156	0.059	6.1	0.76	0.94	4
Soybean	CT	2005–2006	1018 (281)	1060 (279)	41	0.254	6.4	0.93	0.98	4
	NT	2005–2006	974 (238)	1090 (239)	115	0.000	11.8	0.69	0.93	4

[a] The measured yields are average values from three replicates.
[b] Data in brackets are s.d.

indicates perfect model performance, a NSE value between 0.0 and 1.0 is generally viewed as acceptable model performance, and a NSE value <0.0 illustrates poor model performance (Moriasi et al., 2007; Schaefli and Gupta, 2007).

The d (0 to 1) index is a dimensionless and bounded measure with higher values indicating better agreement between simulation and measurement (Willmott, 1982; Krause et al., 2005). Based on the recommendation of Liu et al. (2013), a value of $d < 0.7$ indicates a "poor" agreement, a value of $0.7 \le d < 0.8$ indicates a "fair" agreement, a value of $0.8 \le d < 0.9$ indicates a "good" agreement, and a value of $d \ge 0.9$ indicates an "excellent" agreement between simulated and measured values.

2.4. Climate change scenarios

Climate change scenarios are often used to make projections of future greenhouse gas (GHG) emissions from agroecosystems and to evaluate vulnerability of agricultural production to climate change. The Representative Concentration Pathways (RCPs) were used in the fifth assessment report of IPCC (2014) as the latest scenarios to make

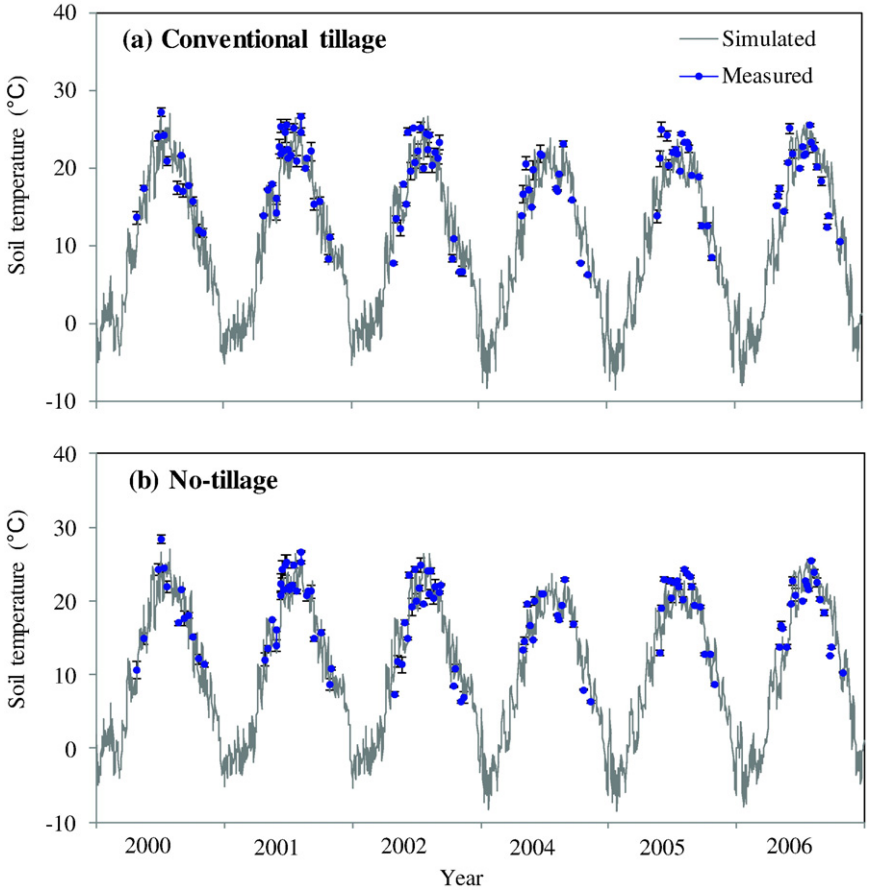

Fig. 2. Simulated and measured soil temperature (0–0.10 m) from 2000 to 2006 under (a) conventional tillage (CT) and (b) no tillage (NT) at Woodslee, ON, Canada. Bars are standard errors (n = 4).

Table 5
Statistical evaluation between the simulated and measured soil temperature, moisture, mineral N and N_2O emissions under conventional tillage (CT) and no tillage (NT) experiments using the DNDC model at Woodslee, ON, Canada.

Variables	Treatment	Time period	Measured	Simulated	MBE	Paired *t* (p)	nRMSE %	NSE	d	Sample no.
Soil temperature (°C)	CT	2000–2002, 2004–2006	18.83 (5.11)[a]	18.1 (4.98)	−0.72	0.012	16.3	0.63	0.90	113
	NT	2000–2002, 2004–2006	18.48 (5.16)	18.1 (4.94)	−0.38	0.159	15.4	0.69	0.91	113
Soil moisture (%)	CT	2000–2002, 2004–2006	21.38 (5.6)	25.22 (5.39)	3.84	0.000	31.5	−0.46	0.66	116
	NT	2000–2002, 2004–2006	22.81 (6.14)	25.25 (5.8)	2.44	0.000	27.7	−0.07	0.71	116
Soil mineral N (kg N ha^{-1})	CT	2005–2006	26.85 (25.7)	28.56 (30.48)	1.71	0.484	31.2	0.88	0.98	10
	NT	2005–2006	24.61 (25.49)	31.57 (28.31)	6.96	0.066	49.4	0.75	0.94	10
Daily N_2O emission (g N ha^{-1})	CT	2000–2002, 2004–2006	14.13 (21.97)	14.43 (24.12)	0.21	0.815	64.4	0.83	0.96	106
	NT	2000–2002, 2004–2006	14.88 (22.85)	16.59 (23.77)	2.70	0.083	115.7	0.50	0.87	106
Cumulative N_2O (kg N ha^{-1})	CT	2000–2002, 2004–2006	4.05 (2.08)	4.11 (1.04)	0.05	0.906	26.5	0.68	0.86	6
	NT	2000–2002, 2004–2006	3.56 (1.74)	4.27 (0.95)	0.60	0.097	29.3	0.58	0.85	6

[a] Data in brackets are s.d.

projections based on different 21st century pathways of GHG and air pollutant emissions, energy and land use, technological development and socio-economic change (Moss et al., 2010; Van Vuuren et al., 2011). There are four RCPs including a stringent mitigation scenario (RCP2.6), two intermediate scenarios (RCP4.5 and RCP6.0) and one scenario with high GHG emissions (RCP8.5) based upon radiative forcing levels of 2.6, 4.5, 6.0 and 8.5 W/m^2 by the end of the 21st century (Van Vuuren et al., 2011; IPCC, 2014).

A new regional climate model CanRCM4, developed at the Canadian Centre for Climate Modelling and Analysis (CCCma) of Environment Canada (Scinocca et al., 2016) has been used to produce downscaled climate information at 50 km and 25 km resolution for domains covering North America, the Arctic, Africa, and Europe as part of an international downscaling effort. In this study, the CanRCM4 was used to generate future climate scenarios RCP4.5 and RCP8.5 at Woodslee, ON, Canada which are medium and high GHG gas emission scenarios with radiative forcing levels of 4.5 and 8.5 w/m^2 at the end of the 21st century, respectively (Van Vuuren et al., 2011). Additionally, bias correction (Qian et al., 2016) was applied to daily outputs from the CanRCM4 to drive the DNDC model. Daily climatic outputs from CanRCM4 were obtained from the CCCma website (http://www.cccma.ec.gc.ca/data/data.shtml) for the historical baseline period from 1971 to 2000 and for the future period from 2071 to 2100. The calibrated cultivar parameters of AC Essex for wheat, N58D1 for maize and 92M91RR for soybean were used in the climate scenario simulations (Table 3).

In this study, the comparison of historical and projected climate variables for Woodslee, Ontario is shown in Fig. 1. The mean annual maximum, minimum and average temperature for the baseline was 13.8, 4.6 and 9.2 °C for Woodslee. Compared to the baseline, the simulated average annual temperature increased by 3.5 °C and 5.7 °C and annual

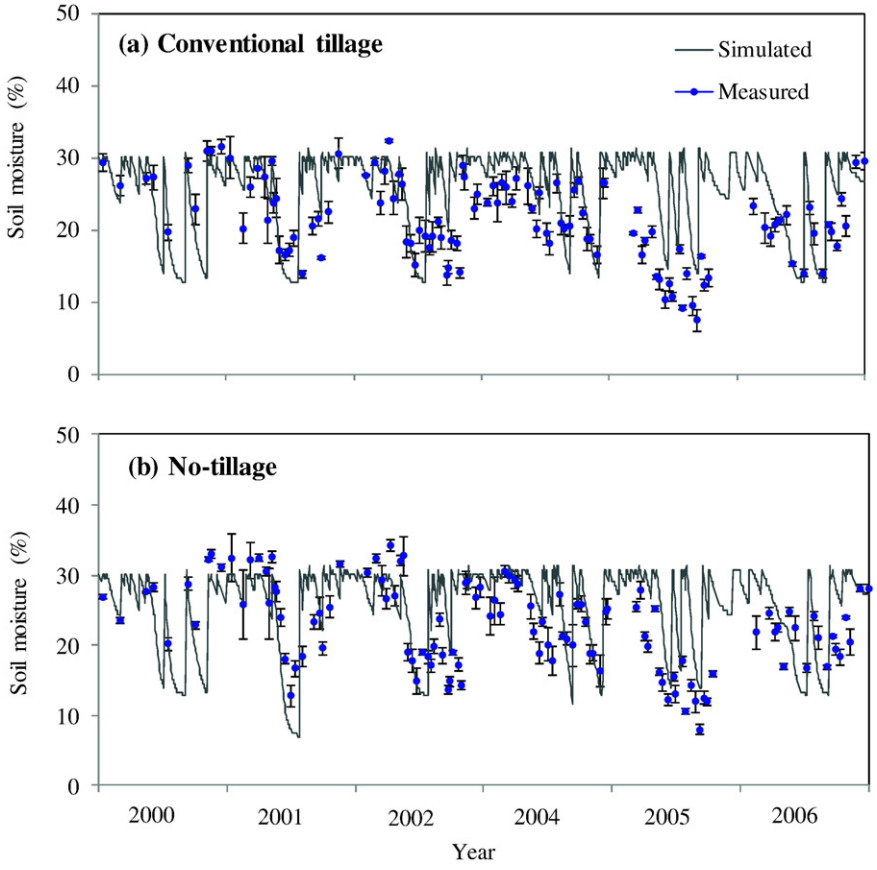

Fig. 3. Simulated and measured soil moisture (0–0.10 m) from 2000 to 2006 under (a) conventional tillage (CT) and (b) no tillage (NT) at Woodslee, ON, Canada. Bars are standard errors (n = 4).

precipitation increased by 20 mm at RCP4.5 scenarios and 97 mm with RCP8.5 scenarios. The average CO_2 concentration for the baseline (1971–2000) was 346 ppm, and it increased to 533(+187) and 807(+461) ppm for RCP4.5 and RCP8.5 scenarios, respectively (Fig. 1). The results can be compared to previous studies using SRES-A2 scenarios in this location. For example, Smith et al. (2013a) stated that the average annual temperature would increase by about 3.5 °C and annual precipitation would increase by about 50 mm in the future period 2041–2070.

3. Results and discussion

3.1. Model calibration and evaluation

3.1.1. Crop yield

The DNDC model simulated crop yields matched the measured values very well for CT treatments from 2000 to 2002 for corn and winter wheat and from 2002 to 2004 for soybean (Fig. S2 and Table 4). The yield agreements for the CT treatment resulted in the following statistics: d index (0.94–0.99), NSE (0.79–0.95) and nRMSE (4.4–5.4%). For NT treatments, the values of d index, NSE and nRMSE ranged from 0.85–0.97, 0.32–0.86 and 2.9–9.9%, respectively, which indicated nearly "excellent" performance between simulated and measured crop yields. These results illustrate that the DNDC model was successfully calibrated (Table 4; Fig. S2).

The DNDC model performance was evaluated using the measured and simulated yields from 2003 to 2006 for corn and winter wheat and from 2005 to 2006 for soybean and it should be noted that these data were different from the data used for model calibration (Fig. S2, Table 4). For CT treatments, the statistical values of d index, NSE and nRMSE were similar to the calibration phases (i.e., d index ranged 0.92–0.98, NSE ranged from 3.4 to 6.4 and nRMSE ranged from 0.69 to 0.93%) indicating "excellent" agreements for all three crop yields. The NT treatments also showed "good" to "excellent" performance for three crops. For example, the values of d index, nRMSE and NSE ranged from 0.86–0.94, 0.54–0.76 and 5.5–11.8%, respectively. The only significant MBE value (115 kg ha^{-1}) for soybean was detected under NT using the paired t ($p < 0.01$) (Table 4). The DNDC estimates also found little or no change in crop yields between the two tillage managements. Drury et al. (1999) showed that NT management could sometimes result in delayed emergence of maize due to lower surface soil temperatures induced by surface residues that would hold water and shade the soil surface. The DNDC model does not presently characterize these effects on germination timing and future developments should better differentiate these treatment effects.

3.1.2. Soil temperature

Soil temperature (0–0.1 m) from 2000 to 2006 was evaluated using the DNDC model (Fig. 2, Table 5). The measured soil temperature was lower under NT treatments compared to CT treatments although these differences were not statistically significant, which were partly attributed to the accumulation of crop residue on the surface of the NT soils (Drury et al., 2012). In the DNDC simulation, the average values of d index, NSE and nRMSE were 0.91, 0.66, 15.9%, respectively, showing "good" to "excellent" agreements for both CT and NT treatments between simulated and measured soil temperatures. However, the simulated soil temperature between CT and NT treatments were the same at 18.1 °C (Table 5) because of the deficiencies in the temperature algorithm which does not consider the insulation effect of surface crop residues in the model. In this study, the average soil temperature was slightly underestimated by about 4% which was in agreement with Smith et al. (2008) and Uzoma et al. (2015).

3.1.3. Soil moisture

The simulated soil water dynamics in the surface soil layer (0–0.1 m) were evaluated using measured values for both CT and NT treatments (Table 5, Fig. 3). For CT treatments, the DNDC model overestimated the simulated soil water contents (MBE = 3.84) compared to the measured data. The nRMSE > 30%, NSE < 0 and d < 0.70 showed "poor" agreement between the simulated and measured soil water contents (Table 5). For NT treatments, the MBE (MBE = 2.44) also showed the simulation overestimated soil water contents. The values of d index, NSE and nRMSE were 0.71, −0.07 and 27.7% which indicates that there was only a "fair" agreement for NT treatments between the simulated and measured soil water contents. The DNDC model showed "poor" or "fair" performances for simulating soil water content mainly because it overestimated the simulated values in 2005 (a dry year). When 2005 soil water content data was excluded from the evaluation, the statistics fell into the "good" range with values of 10% < nRMSE < 20%, NSE > 0, as well as d index of 0.79 for both CT and NT treatments.

The DNDC model overestimated soil water content during dry conditions probably as a result of the inability of DNDC to characterize preferential flow through clay cracks (Uzoma et al., 2015). In Brookston clay soils in Southwestern Ontario, it has been reported that cracking (shrinking/swelling) occurred in the clay soils under low soil water conditions based on field measurements. These cracks transport precipitation by preferential flow into the soil profile quickly which would lead to increased drainage (Technical report, 1990). However, the lack of measured field data on the timing and extent of clay cracking is a limitation to the development and calibration of an appropriate algorithm (Smith et al., 2008; Uzoma et al., 2015).

3.1.4. Soil mineral N

The simulated soil mineral N (0–0.3 m) was evaluated using the measured data from 2005 to 2006 (Fig. 4). Although the d index (0.94–0.98) and NSE (0.75–0.88) showed "excellent" agreement between the simulated and measured soil mineral N, the nRMSE values of 31.2–49.4% indicated that the soil mineral N varied substantially

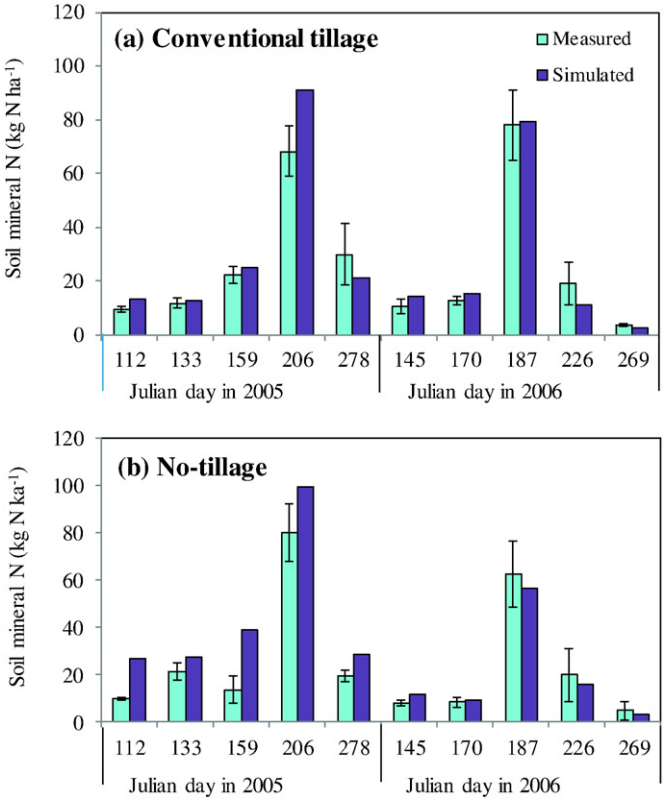

Fig. 4. Simulated and measured soil mineral N (0–0.30 m) from 2005 to 2006 under (a) conventional tillage (CT) and (b) no tillage (NT) at Woodslee, ON, Canada. Bars are standard error (n = 4).

between the simulated and measured soil mineral N (Table 5). In addition, the values of MBE (1.71–6.96 kg N ha^{-1}) indicated that the simulation overestimated soil mineral N especially for NT treatment, but no statistical significant difference based on paired *t*-test. The results were agreement with the study of Abdalla et al. (2014) which illustrated that the DNDC model had a poor estimation on soil N in absolute values as well as over space and time. In this study, the DNDC poorly estimated the distribution of soil mineral N in a 0–0.3 m soil layer under different tillage systems which was partly attributed to the flaws in soil water balance module (a simple cascade approach) that could affect the water and nutrient upward flow and downward infiltration, especially under dry soil conditions where preferential flow through cracks can occur.

3.1.5. N_2O emissions

Simulated and measured daily N_2O emissions for CT and NT treatments from 2000 to 2006 (Fig. 5) were greatest after fertilizer application following high precipitation events. For both CT and NT treatments, the values of the d index ranged from 0.87–0.96 and NSE ranged from 0.50–0.83 which indicates that there was "good" agreements between the simulated and measured N_2O emissions (Table 5). However, nRMSE values were 64.4% for CT and 116% for NT, indicating a greater daily temporal variation of the N_2O emissions between the simulation and measured values. For cumulative seasonal N_2O emissions, all the statistics (nRMSE < 30%, NSE > 0.58, d > 0.85) indicated that the DNDC model had a good performance (Table 5). The results were in agreement with other studies which reported that the DNDC model simulated N_2O very well for the cumulative emissions (Smith et al., 2008; Ludwig et al., 2011; Uzoma et al., 2015) but large temporal variations in estimating daily N_2O emission (Table 5). In addition, the DNDC model overestimated N_2O emissions especially for NT treatment (by 17.4%) in 2005 (a dry year) which could be attributed to the overestimation in soil mineral N (MBE = 7.0 kg N ha^{-1}) and soil water content (Fig. 4 and Table 5). In this DNDC simulation, over-predicted soil water contents resulted in a high rate of decomposition and release of greater quantities of substrates that could enhance denitrification (Metay et al., 2011). In dry years it is possible that there was not enough DOC available for denitrification reactions and carbon decomposition is usually slower under NT. Nitrous oxide emissions increase with rising soil temperature due to the fact that rates of enzymatic and microbial processes generally increase with temperature (Smith et al., 1998). However, the model did not capture the temperature difference between CT and NT that was apparent from the field measurements.

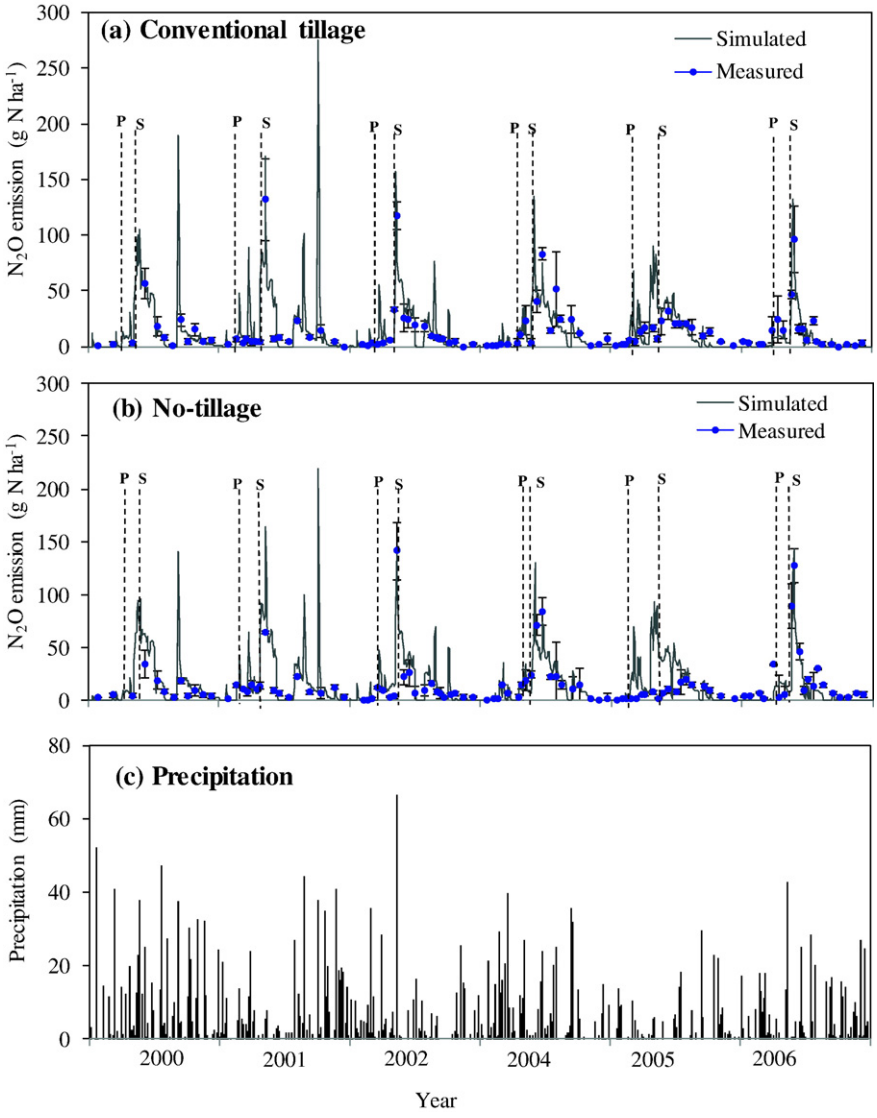

Fig. 5. Simulated and measured daily N_2O emissions from 2000 to 2006 under (a) conventional tillage (CT), (b) no tillage (NT) and (c) precipitation at Woodslee, ON, Canada. Bars are standard error (n = 4). The dash lines correspond to the dates for the N applications of planting (P) and sidedress (S).

3.2. Climate change impacts on crop yields and N_2O emissions

3.2.1. Climate change impacts on crop yields

The impacts of climate change on crop yields were evaluated by comparing historical (1971–2000) yields and future years' predications (2071–2100) under CT and NT treatments at Woodslee, ON (Fig. 6). When CO_2 concentrations were at baseline levels in the scenarios, winter wheat yields significantly decreased by 15.8% for CT and by 15.9% for NT at RCP4.5 scenarios whereas they decreased by 32% for CT and 32.1% for NT with RCP8.5 scenarios. Neither future climate change scenario had a notable impact on soybean yield for both CT and NT treatments at the baseline CO_2 levels. However, the maize yields increased by 11.7% for CT and by 9.3% for NT under the RCP4.5 scenario and they increased by 17.1% for CT and by 13.9% for NT under the RCP8.5 scenarios. These yield increases were in response to the higher optimum temperature (30 °C) for maize grain growth compared to soybean (25 °C).

When the effect of increased CO_2 was taken into consideration, average soybean yields significantly increased by 17.4% and 33.5% under RCP4.5 and RCP8.5 scenarios, respectively. Increased CO_2 levels also reduced the negative effects on winter wheat yields from climate change. However, the increased CO_2 levels did not have a notable impact on maize yields. The results can be attributed to the different crop types (wheat and soybean are C3 crops and maize is a C4 crop). Hatfield et al. (2011) concluded that the doubling of CO_2 resulted in about a 30% increase in C3 crop yields, compared to less than a 10% increase for C4 crops. Thomson et al. (2005) and Ko et al. (2012) reported similar results saying that the increased mean temperature had a negative effect on crop yield, which was partially offset by the positive impacts associated with increasing CO_2. Makowski et al. (2015) used meta-models to calculate CO_2 and temperature thresholds leading to yield gain and loss and they indicated that climate change had a positive effect on wheat yield if CO_2 concentration increased by at least 117 ppm depending on the site and if temperature concurrently increased by 2 °C. For maize, however, the required CO_2 increases were found to be much higher.

Crops tend to grow faster in warmer conditions, but faster growth reduces the amount of time that seeds have to mature. Therefore, crop cultivars under future increased temperature conditions require a longer growing season to reach maturity for obtaining high yield. In this study, we evaluated cultivars which required increased TDD (thermal degree days) including winter wheat (TDD 1800), maize (TDD 3100) and soybean (TDD 2000). Winter wheat yields with the new cultivar significantly increased yield under CT by 27.1% and under NT by 33.7%

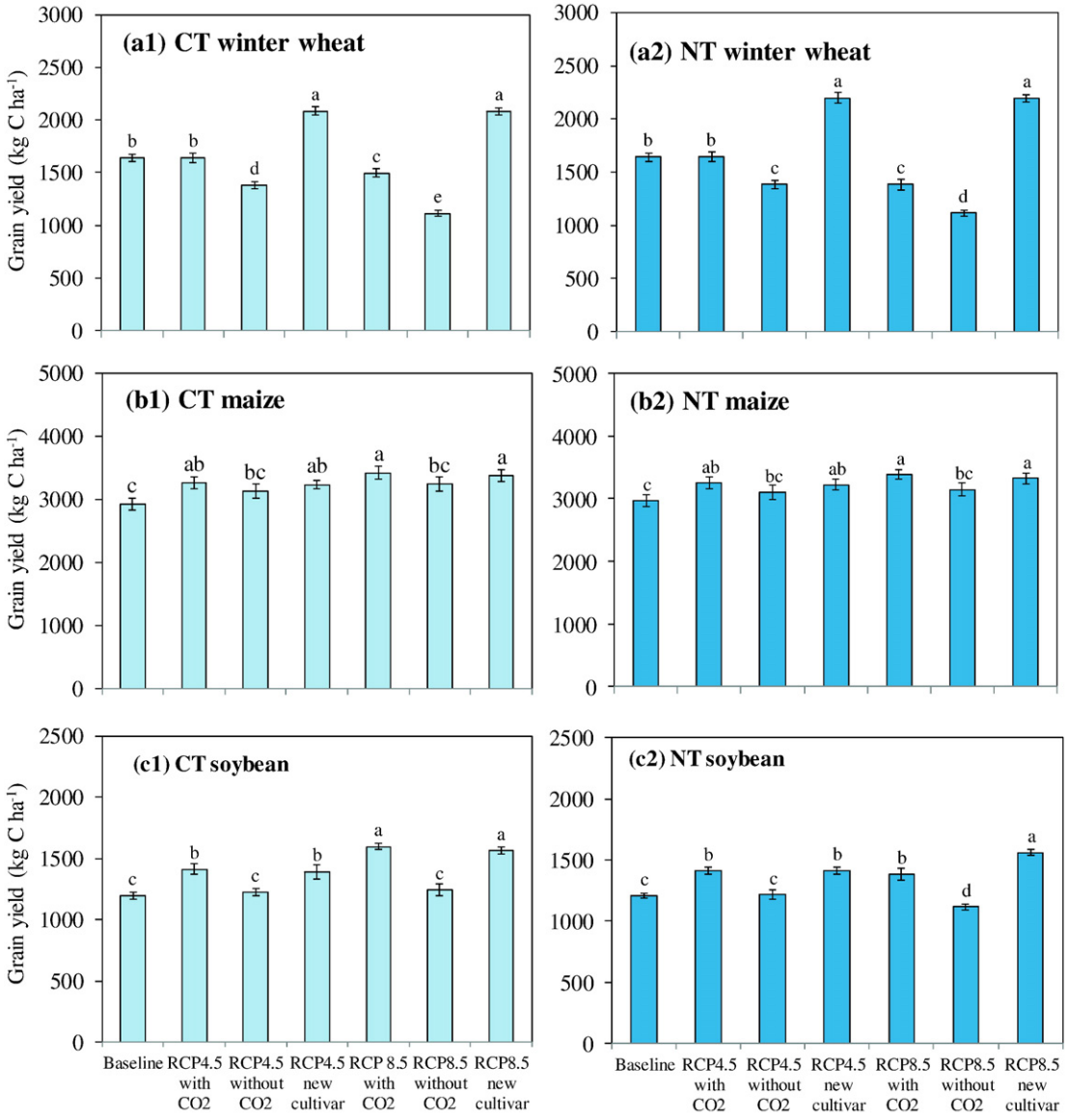

Fig. 6. The impacts of climate change on yields of (a) winter wheat, (b) maize and (c) soybean under conventional tillage (CT) and no tillage (NT) at Woodslee, ON, Canada. Bars are standard errors. Lowercase letters represent significant differences at $p < 0.05$.

for the RCP4.5 scenario whereas they increased CT yields by 26.9% and NT yields by 33.5% with RCP8.5 scenarios compared to the current cultivars (TDD 1300), (Fig. 6). However, there were no notable differences between current and new cultivars with different TDDs for maize (2900 vs. 3100) and soybean (1500 vs. 2000) possibly due to no significant heat stress for calibrated current cultivars under both RCP4.5 and RCP8.5 climate scenarios

3.2.2. Climate change impacts on N_2O emissions

A comparison of the N_2O emissions between historical and future climate scenarios was carried out for CT and NT treatments (Fig. 7). Using the baseline CO_2 concentrations, the mean annual N_2O emissions for CT treatments significantly increased by 56.1%, for winter wheat, 10.7% for maize and 44.6% for soybean for RCP4.5 whereas it increased by 87.6%, 9.5% and 31.2% for wheat, maize and soybean, respectively under RCP8.5. The mean annual N_2O emissions under NT only increased for winter wheat (19.2% for RCP4.5 and 31.7% for RCP8.5) whereas no significant differences were found for maize and soybean compared to the baseline scenario. The results for CT were in agreement with other studies which illustrated that N_2O emissions would increase in North America under future climate scenarios (Del Grosso and Parton, 2012; Tian et al., 2012; Smith et al., 2013a). However in this study NT was found to be a viable management practice to control N_2O emissions under future climate change conditions especially for corn and soybean.

Increased CO_2 concentrations had a positive effect on reducing N_2O emissions (only significant for winter wheat under CT, Fig. 7) compared to the baseline CO_2 concentrations under future climate change scenarios RCP4.5 and RCP8.5. High atmospheric CO_2 concentrations can lead to increases in crop growth especially for winter wheat (C3 crops), and improved water and nitrogen use efficiency leaving less excess N available in the soil for N_2O emissions (Rogers et al., 1999; Kimball et al., 2002) and these effects were captured by the modified DNDC model (Smith et al., 2013a).

Compared to current cultivars, when the new winter wheat cultivar was evaluated, N_2O emissions were significantly reduced by 32.5% for CT and 25.1% for NT with the RCP4.5 scenario whereas they decreased by 35.9% for CT and 33.9% for NT with the RCP8.5 scenario. There were also trends for decreased N_2O emissions for new maize (7.5% decrease) and soybean (3.3% decrease) compared to current cultivars under future climate scenarios. These decreases in N_2O emissions were due to higher

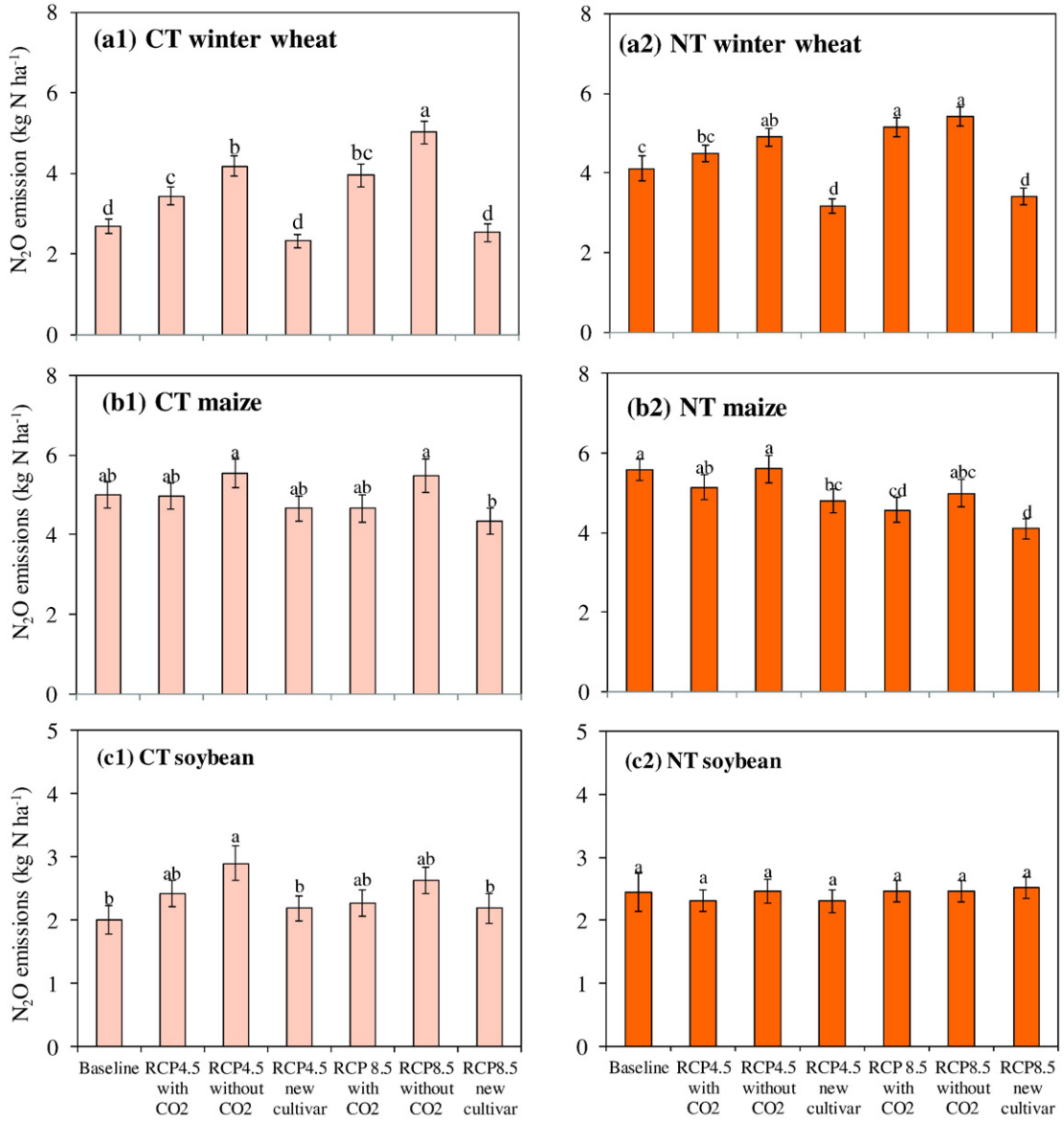

Fig. 7. The impacts of climate change on N_2O emissions of (a) winter wheat, (b) maize and (c) soybean under conventional tillage (CT) and no tillage (NT) at Woodslee, ON, Canada. Bars are standard errors. Lowercase letters represent significant differences at $p < 0.05$.

crop heat units and longer growing season lengths which contributed to more biomass accumulation and extended inorganic N uptake (Smith et al., 2013b). Therefore, the results suggest that development of higher TDD cultivars in the future could have the co-benefit of increasing crop yields along with reducing N_2O emissions.

4. Conclusions

A regionalized DNDC model (DNDC v.CAN) was calibrated and evaluated using measured crop yields, soil temperature, moisture and N_2O emissions for a winter wheat-maize-soybean rotation system under conventional and no tillage practices at Woodslee, Ontario, Canada. The calibrated DNDC model was then used to explore the impacts of climate change on crop yields and N_2O emissions under RCP4.5 and RCP8.5 scenarios (2071–2100).

The results showed "good" to "excellent" agreements between simulated and measured crop yields for both CT and NT practices. There were no differences in simulated soil temperature between CT and NT treatments because of the deficiencies in the temperature algorithm which do not consider the insulation effect of surface crop residues in the model which is characteristic of the NT system especially at the beginning of the growing season. In addition, the DNDC model provided a reasonable prediction of soil water contents (0–0.1 m), but it overestimated water contents during dry conditions because the model was unable to characterize preferential flow through cracks in the clay loam soil. The statistics showed "good" agreement between the simulated and measured N_2O emissions. However, the DNDC model overestimated N_2O emissions especially for NT treatment (by 17.4%) in 2005 which could be partly attributed to the overestimation in soil mineral N and soil water content in 2005 (a dry year).

Soybean and wheat yields were significantly increased under the future climate scenarios compared to the baseline scenarios. In addition, the mean annual N_2O emissions for winter wheat were predicted to significantly increase under future RCP scenarios. Compared to current cultivars, there was a notable reduction in N_2O emissions for new wheat cultivars (higher TDD) under future climate conditions because higher crop heat units and longer growing seasons contribute to more biomass accumulation and enhanced inorganic N uptake. Therefore, our study suggests that longer season cultivars with greater heat requirements should be considered in the future to increase crop yield and potentially reduce N_2O emissions.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.agsy.2017.01.025.

References

Abdalla, M., Wattenbach, M., Smith, P., Ambus, P., Jones, M., Williams, M., 2009. Application of the DNDC model to predict emissions of N_2O from Irish agriculture. Geoderma 151, 327–337.

Abdalla, M., Hastings, A., Helmy, M., et al., 2014. Assessing the combined use of reduced tillage and cover crops for mitigating greenhouse gas emissions from arable ecosystem. Geoderma 223–225, 9–20.

Beheydt, D., Boeck, P., Ahmed, H.P., Van Cleemput, O., 2008. N_2O emission from conventional and minimum-tilled soils. Biol. Fertil. Soils 44, 863–873.

Chen, Y., Liu, S., Li, H., Song, X.F., Li, C.Y., Cruse, R.M., Zhang, X.Y., 2011. Effects of conservation tillage on corn and soybean yield in the humid continental climate region of Northeast China. Soil Tillage Res. 115-116, 56–61.

Chi, J., Waldo, S., Pressley, S., O'Keeffe, P., Huggins, D., Stöckle, C., Pan, W.L., Brooks, E., Lamb, B., 2016. Assessing carbon and water dynamics of no-till and conventional tillage cropping systems in the inland Pacific Northwest US using the eddy covariance method. Agric. For. Meteorol. 218–219, 37–49.

Del Grosso, S.J., Parton, W.J., 2012. Climate change increases soil nitrous oxide emissions. New Phytol. 196 (2), 327–328.

Deng, Q., Hui, D., Wang, J., Yu, C.-L., Li, C., Reddy, K.C., Dennis, S., 2016. Assessing the impacts of tillage and fertilization management on nitrous oxide emissions in a cornfield using the DNDC model. J. Geophys. Res. Biogeosci. http://dx.doi.org/10.1002/2015JG003239.

Drury, C.F., Tan, C.S., Welacky, T.W., Oloya, T.O., Hamill, A.F., Weaver, S.E., 1999. Red clover and tillage influence on soil temperature, water content, and corn emergence. Agron. J. 91, 101–108.

Drury, C.F., Reynolds, W.D., Tan, C.S., Welacky, T.W., Calder, W., McLaughlin, N.B., 2006. The influence of conservation tillage and nitrogen management strategies on nitrous oxide emissions from Eastern Canada. Soil Sci. Soc. Am. J. 70, 570–581.

Drury, C.F., Yang, X.M., Reynolds, W.D., McLaughlin, N.B., 2008. Nitrous oxide and carbon dioxide emissions from monoculture and rotational cropping of corn, soybean and winter wheat. Can. J. Soil Sci. 88:163–174. http://dx.doi.org/10.4141/CJSS06015.

Drury, C.F., Reynolds, W.D., Yang, X.M., McLaughlin, N.B., Welacky, T.W., Calder, W., Grant, C.A., 2012. Nitrogen source, application time and tillage effects on soil nitrous oxide emissions and corn grain yields. Soil Sci. Soc. Am. J. 76 (4):1268–1279. http://dx.doi.org/10.2136/sssaj2011.0249.

Farahbakhshazad, N., Dinnes, D.L., Li, C.S., Jaynes, D.B., Salas, W., 2008. Modeling biogeochemical impacts of alternative management practices for a row-crop field in Iowa. Agric. Ecosyst. Environ. 123, 30–48.

Hatfield, J.L., Boote, K.J., Kimball, B.A., Ziska, L.H., Izaurralde, R.C., Ort, D., Thomson, A.M., Wolfe, D., 2011. Climate impacts on agriculture: implications for crop reduction. Agron. J. 103, 351–370.

He, W., Yang, J.Y., Zhou, W., Drury, C.F., Yang, X.M., Reynolds, W.D., Wang, H., He, P., Li, Z.T., 2016. Sensitivity analysis of crop yields, soil water contents and nitrogen leaching to precipitation, management practices and soil hydraulic properties in semi-arid and humid regions of Canada using the DSSAT model. Nutr. Cycl. Agroecosyst. 106, 201–215.

Huggins, D.R., Reganold, J.P., 2008. No-till: the quiet revolution. Sci. Am. 299 (1), 70.

IPCC, 2014. Climate Change: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland.

Islam, A., Ahuja, L.R., Garcia, L.A., Ma, L., Saseendran, A.S., Trout, T.J., 2012. Modeling the impacts of climate change on irrigated corn production in the Central Great Plains. Agric. Water Manag. 110, 94–108.

Jeuffroy, M.H., Casadebiag, P., Debaeke, P., Loyce, C., Meynard, L.M., 2013. Agronomic model uses to predict cultivar performance in various environments and cropping systems. A review. Agron. Sustain. Dev. http://dx.doi.org/10.1007/s13593-013-0170-9.

Kimball, B.A., Kobayashi, K., Bindi, M., 2002. Response of agriculture crops to free-air CO_2 enrichment. Adv. Agron. 77, 293–368.

Ko, J.H., Ahuja, L.R., Saseendran, S.A., Green, T.R., Ma, L., Nielsen, D.C., Walthall, C.L., 2012. Climate change impacts on dryland cropping systems in the Central Great Plains, USA. Clim. Chang. 111, 445–472.

Krause, P., Boyle, D.P., Bäse, F., 2005. Comparison of different efficiency criteria for hydrological model assessment. Adv. Geosci. 5, 89–97.

Li, C., Frolking, S., Frolking, T.A., 1992a. A model of nitrous oxide evolution from soil driven by rainfall events: 1. Model structure and sensitivity. J. Geophys. Res. 97, 9759–9776.

Li, C., Frolking, S., Frolking, T.A., 1992b. A model of nitrous oxide evolution from soil driven by rainfall events: 2. Model application. J. Geophys. Res. 97, 9777–9783.

Li, H., Qiu, J., Wang, L., Tang, H., Li, C.S., Van Ranst, E., 2010. Modelling impacts of alternative farming management practices on greenhouse gas emissions from a winter wheat–maize rotation system in China. Agric. Ecosyst. Environ. 135, 24–33.

Li, C., Salas, W., Zhang, R., Krauter, C., Rotz, A., Mitloehner, 2012. Manure-DNDC: a biogeochemical process model for quantifying greenhouse gas and ammonia emissions from livestock manure systems. Nutr. Cycl. Agroecosyst. 93, 163–200.

Li, Z.T., Yang, J.Y., Drury, C.F., Hoogenboom, G., 2015a. Evaluation of the DSSAT-CSM for simulating yield and soil organic C and N of a long-term maize and wheat rotation experiment in the Loess Plateau of Northwestern China. Agric. Syst. 135, 90–104.

Li, Z.T., Yang, J.Y., Smith, W.Z., Drury, C.F., Lemke, R.L., Grant, B., He, W.T., Li, X.G., 2015b. Simulation of long-term spring wheat yields, soil organic C, N and water dynamics using DSSAT-CSM in a semi-arid region of the Canadian prairies. Nutr. Cycl. Agroecosyst. 101, 401–419.

Liu, H.L., Yang, J.Y., Drury, C.F., Reynolds, W.D., Tan, C.S., Bai, Y.L., He, P., Jin, J., Hoogenboom, G., 2011. Using the DSSAT-CERES-Maize model to simulate crop yield and nitrogen cycling in fields under long-term continuous maize production. Nutr. Cycl. Agroecosyst. 89:313–328. http://dx.doi.org/10.1007/s10705-010-9396-y.

Liu, S., Yang, J.Y., Zhang, X.Y., Drury, C.F., Reynolds, W.D., Hoogenboom, G., 2013. Modelling crop yield, soil water content and soil temperature for a soybean-maize rotation under conventional and conservation tillage systems in Northeast China. Agric. Water Manag. 123, 32–44.

Long, S.P., Marshall-Colon, A., Zhu, X.G., 2015. Meeting the global food demand of the future by engineering crop photosynthesis and yield potential. Cell 161 (1), 56–66.

Ludwig, B., Bergstermann, A., Priesack, E., Flessa, H., 2011. Modelling of crop yields and N_2O emissions from silty arable soils with differing tillage in two long-term experiments. Soil Tillage Res. 112, 114–121.

Makowski, D., Asseng, S., Ewert, F., et al., 2015. A statistical analysis of three ensembles of crop model responses to temperature and CO_2 concentration. Agric. For. Meteorol. 214–215, 483–493.

McLaughlin, N.B., Drury, C.F., Reynolds, W.D., Yang, X.M., Li, Y.X., Welacky, T.W., Stewart, G., 2008. Energy inputs for conservation and conventional primary tillage systems in a clay loam soil. Trans. ASABE 51, 1153–1163.

Metay, A., Chapuis-Lardy, L., Findeling, A., Oliver, R., Alves Moreira, J.A., Feller, C., 2011. Simulating N_2O flues from a Brazilian cropped soil with contrasted tillage practices. Agric. Ecosyst. Environ. 140, 255–263.

Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Bingner, R.L., Harmel, R.D., Veith, T., 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Trans. ASABE 50, 885–900.

Moss, R.H., Edmonds, J.A., Hibbard, K.A., Manning, M.R., Rose, S.K., van Vuuren, D.P., Carter, T.R., Emori, S., Kainuma, M., Kram, T., 2010. The next generation of scenarios for climate change research and assessment. Nature 463, 747–756.

Nash, J.E., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models part I-a discussion of principles. J. Hydrol. 10, 282–290.

Priesack, E., Gayler, S., Hartmann, H.P., 2006. The impact of crop growth sub-model choice on simulated water and nitrogen balances. Nutr. Cycl. Agroecosyst. 75, 1–13.

Qian, B., De Jong, R., Huffman, T., Wang, H., Yang, J.Y., 2016. Projecting yield changes of spring wheat under future climate scenarios on the Canadian Prairies. Theor. Appl. Climatol. 123, 651–669.

Rochette, P., Worth, D.E., Lemke, R.L., McConkey, B.G., Pennock, D.J., Wagner-Riddle, C., Desjardins, R.L., 2008. Estimation of N_2O emissions from agricultural soils in Canada. I. Development of a country-specific methodology. Can. J. Soil Sci. 88, 641–654.

Rogers, H.H., Runion, G.B., Prior, S.A., 1999. Response of plants to elevated atmospheric CO_2: root growth, mineral nutrition, and soil carbon [M]. In: Luo, Y., Mooney, H.A. (Eds.), Carbon Dioxide and Environmental Stress. Academic Press, San Diego, CA, pp. 215–244.

Schaefli, B., Gupta, H.V., 2007. Do Nash values have value? Hydrol. Process. http://dx.doi.org/10.1002/hyp.6825.

Scinocca, J.F., Kharin, V.V., Jiao, Y., Qian, M.W., Lazare, M., Solheim, L., Flato, G.M., Biner, S., Desgagne, M., Dugas, B., 2016. Coordinated global and regional climate modelling. J. Clim. 29, 17–35.

Shi, X.H., Yang, X.M., Drury, C.F., Reynolds, W.D., McLaughlin, N.B., Zhang, X.P., 2012. Impact of ridge tillage on soil organic carbon and selected physical properties of a clay loam in Southwestern Ontario. Soil Tillage Res. 120, 1–7.

Smith, K.A., Thomson, P.E., Clayton, H., McTaggard, I.P., 1998. Effects of temperature, water content and nitrogen fertilisation on emissions of nitrous oxide by soils. Atmos. Environ. 32, 3301–3309.

Smith, W.N., Grant, B.B., Desjardins, R.L., Rochette, P., Drury, C.F., Li, C., 2008. Evaluation of two process-based models to estimate soil N_2O emissions in Eastern Canada. Can. J. Soil Sci. 88, 251–260.

Smith, W.N., Grant, B.B., Desjardins, R.L., Kroebel, R., Li, C., Qian, B., Worth, D.E., McConkey, B.G., Drury, C.F., 2013a. Assessing the effects of climate change on crop production and GHG emissions in Canada. Agric. Ecosyst. Environ. 179, 139–150.

Smith, C.M., David, M.B., Mitchell, C.A., Masters, M.D., Anderson-Teixeira, K.J., Bernacchi, C.J., DeLucia, E.H., 2013b. Reduced nitrogen losses after conversion of row crop agriculture to perennial biofuel crops. J. Environ. Qual. 42 (1):219–228. http://dx.doi.org/10.2134/jeq2012.0210.

Technical report, 1990. Survey of Moisture Distribution Between Tile Drainage Laterals and Its Relationship To Compaction and Rooting Depth in Flat Clay Soils. Agriculture Canada (DSS File No. 02 SE 01686-8-TED-19).

Thomson, A.M., Brown, R.A., Rosenberg, N.J., Izaurralde, R.C., Benson, V., 2005. Climate change impacts for the conterminous USA: an integrated assessment. Part. 3. Dryland production of grain and forage crops. Clim. Chang. 69, 43–65.

Tian, H., Lu, C., Chen, G., Tao, B., Pan, S., Del Grosso, S.J., Xu, X., Bruhwiler, L., Wofsy, S.C., Kort, E.A., Prior, S.A., 2012. Contemporary and projected biogenic fluxes of methane and nitrous oxide in North American terrestrial ecosystems. Front. Ecol. Environ. 10 (10), 528–536.

Tsuji, G.Y., Hoogenboom, G., Thornton, P.K., 1998. Understanding Options for Agricultural Production. Kluwer Academic Publishers, Dordrecht, the Netherlands.

Uzoma, K.C., Smith, W., Grant, B., Desjardins, R.L., Guo, X., Hanis, K., Tenuta, M., Goglio, P., Li, C., 2015. Assessing the effects of agricultural management on nitrous oxide emissions using flux measurements and the DNDC model. Agric. Ecosyst. Environ. 206, 71–83.

Van Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V., Lamarque, J., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S.J., Rose, S.K., 2011. The representative concentration pathways: an overview. Clim. Chang. 109 (1–2), 5–31.

Wang, W., Yua, Z., Zhang, W., Shao, Q., Zhang, Y., Luo, Y., Jiao, X., Xu, J., 2014. Responses of rice yield, irrigation water requirement and water use efficiency to climate change in China: historical simulation and future projections. Agric. Water Manag. 146, 249–261.

Wang, Z., Qi, Z., Xue, L., Bukovsky, M., Helmers, M.J., 2015. Modeling the impacts of climate change on nitrogen losses and crop yield in a subsurface drained field. Clim. Chang. http://dx.doi.org/10.1007/s10584-015-1342-1.

Willmott, C.J., 1982. Some comments on the evaluation of model performance. Bull. Am. Meteorol. Soc. 63, 1309–1313.

Willmott, C.J., Ackleson, S.G., Davis, R.E., Feddema, J.J., Klink, K.M., Legates, D.R., Donnell, J.O., Rowe, C.M., 1985. Statistics for the evaluation and comparison of models. J. Geophys. Res. 90, 8995–9005.

Xu-Ri, Prentice, C., Spahni, R., Niu, H.S., 2012. Modelling terrestrial nitrous oxide emissions and implications for climate feedback. New Phytol. 196 (2), 472–488.

Yang, J., Greenwood, D.J., Rowell, D.L., Wadsworth, G.A., Burns, I.G., 2000. Statistical methods for evaluating a crop nitrogen simulation model NABLE. Agric. Syst. 64, 37–53.

Yang, X.M., Drury, C.F., Reynolds, W.D., Tan, C.S., 2008. Impacts of long-term and recently imposed tillage practices on the vertical distribution of soil organic carbon. Soil Tillage Res. 100, 120–124.

Ziadi, N., Angers, D.A., Gagnon, B., Lalande, R., Morel, C., Rochette, P., Chantigny, M.H., 2014. Long-term tillage and synthetic fertilization affect soil functioning and crop yields in a corn-soybean rotation in eastern Canada. Can. J. Soil Sci. 94 (3), 365–376.